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A DEVICE FOR THE DIRECT MEASUREMENT OF UNSTEADY AIR FLOWS AND SOME CHARACTERISTICS OF BOUNDARY LAYER TRANSITION

By

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U. S. ARMY TRANSPORTATION RESEARCH COMMAND

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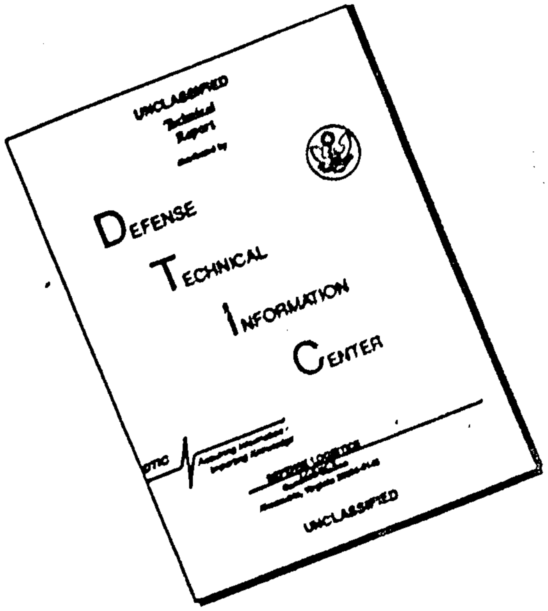

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Aerophysics Research Note No. 24

Prepared by
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for
U. S. ARMY TRANSPORTATION RESEARCH COMMAND
FORT EUSTIS, VIRGINIA

ABSTRACT

A device for use in obtaining instantaneous velocity profiles of unsteady air flows is described. The techniques for its use are illustrated by two typical examples in laminar and turbulent boundary layers.

CONTENTS

ILLUSTRATIONS

INTRODUCTION

The instrumentation used in the study of fluid flows generally measures the time-average, or mean, velocity of the flows involved. For flows which are time-dependent, these techniques are very satisfactory, and such instrumentation has also been used with remarkable success in flows which do vary with time. The turbulent boundary layer, for example, has been examined for years by the use of boundary layer rakes, or probes, which consist, for the most, of simple Pitot-static tubes. The hot-wire anemometer, of course, has been extensively used to measure the fluctuating quantities in the turbulent boundary layer. Besides its rather formidable complexity, the hot-wire anemometer has a further disadvantage in that flow properties can be measured at only one point, or, at best, a few points, in the flow simultaneously.

The use of dyes or stains to visualize the characteristics of a flowing liquid has long been practiced. Probably the earliest experiment of significance is that of Reynolds, who used a thin filament of dye to picture the transition from laminar to turbulent flow. More recently, researchers have ejected colored dye from orifices in the surfaces of bodies submerged in water to delineate the flow patterns around these bodies.

These methods have been extended to use in wind tunnels or smoke tunnels by many researchers. Notably, Brown (Reference 1) has been very successful in picturing flows by means of smoke filaments. In general, however, these techniques are intended to make visible the stream lines of the flow rather than to measure velocities. Head (Reference 3) has also ejected smoke into the turbulent boundary layer of various models in order to study the intermittence of turbulence.

One successful technique for measuring velocity profiles in flowing liquids was developed by Wortman (Reference 5), who discharged an electrical current through tellurium wires and photographically recorded the resulting streaks which were formed in the fluid. Later, Geller (Reference 2) developed a similar technique, in which velocity profiles were visualized by oxygen bubbles shed from a wire through the electrolysis of the water caused by the passage of a rather high current through the wire.

In the early 1950's, Dr. August Raspet and Mr. Thomas S. Moore of the Aerophysics Department of Mississippi State University extended this technique to use in air. A thin wire, coated with oil and suddenly heated by the passage of a large electrical current discharged from a condenser, was used to measure, by means of the resulting oil smoke, the velocity profiles within a channel.

The present report describes subsequent refinements and modifications to this technique.

DESCRIPTION OF APPARATUS

The equipment used in this method consists of three main components: a thin wire with its supports, which is mounted in the air flow; an electrical condenser with its controls and power source to provide the properly regulated current to the wire; and a camera with electronic flash attachment to record the velocity profiles depicted by the smoke generated by the wire. (Figure 1)

The present experiments made use of a nichrome wire 0.0015 inch in diameter and approximately 2.0 inches long. A support of berylium copper strips, approximately 0.025 inch thick and 0.20 inch wide, maintained a slight tension in the wire. The supports at each end of the wire, which were given a streamline cross section in the flow direction to minimize disturbances, also served to conduct the electrical current to the wire. Electrical leads connected to the supports were attached to the control box and power source.

The electrical charge to be used was stored in a condenser, which could be discharged through the wire by means of a manual switch. The passage of the resulting rather high current heated the wire very rapidly and caused the oil with which the wire had been coated to vaporize. This oil smoke was then carried downstream at the local velocity of the flow as it passed across the wire. A short time later, approximately several milliseconds, the resulting smoke was brightly illuminated by an electronic flash and was simultaneously photographed. The photograph obtained in this manner thus recorded the velocity profiles of the flow across the wire. The circuit diagram of this equipment is shown in Figure 2.

The circuit shown was designed to produce a thin line of smoke and, after a short delay, to fire a strobeflash to supply the light needed to take a picture of this smoke.

The key, S_1, referred to in the circuit diagram, is normally open, and it is closed to cause the cycle to begin. With the key open, relay K_1 is inactive; this allows capacitor C_1 to charge to a voltage of 180 volts. When the key is closed, relay K_1 is activated, and C_1 discharges through the resistance wire and causes smoke to be produced. The time constant of this loop is approximately 100 microseconds. Another pair of contacts of the relay K_1 triggers the delay circuit. The amount of delay is determined by the time constant $(R_3 + R_4)(C_2)$. The delay is adjustable from 4 milliseconds to 12 milliseconds with the components used.

Time measurements for calibration of the delay circuit were made on an oscilloscope. The voltage pulse of the resistance wire was used to trigger the sweep circuit of the oscilloscope, and a photo-electric cell was used to indicate when the strobeflash fired.

DISCUSSION

In order to determine the applicability and accuracy of this method of flow visualization, the probe was used to measure a laminar boundary layer profile on a flat plate with zero pressure gradient. A photograph of the resulting profile is shown in Figure 3. By projecting and enlarging the negative of this picture in a microfilm viewer, the velocities indicated were measured at various heights, and the velocity profile was determined. The velocities measured in this manner are shown in nondimensional form in comparison to the classical Blasius laminar boundary theory.

Two observers independently measured the example profile shown, and it can be seen that good agreement with theory was obtained in both cases. The actual values of velocities were deduced from a knowledge of the height of the wire and the time delay between the generation of the smoke and the taking of the picture. Several photographs taken at the same position and under the same conditions also showed good repeatability of the process.

With this good agreement found in the steady-state laminar flow condition, the apparatus was next mounted in the turbulent boundary layer of a plate in a zero pressure gradient. The wire was located approximately 6.0 feet downstream of the leading edge of the plate, and the free-stream velocity was maintained at approximately 8.0 feet per second. Under these conditions the boundary layer had only just completed transition to turbulent flow. Slightly upstream of this position, evidence of the Tollmien-Schlichting waves during transition could be seen in smoke filaments allowed to flow parallel to the plate.

Observations of smoke profiles made at the 6.0-foot position indicated strong velocity fluctuations in the boundary layer, and no two profiles observed had the same, or even similar, shapes. Therefore, a number photographs, 21 in all, were made consecutively under identical conditions. Typical examples of this series are shown in Figure 4. The velocities at various heights were measured from each of these photographs, and, with the use of all of the photographs the average velocity at each height was computed. The resulting average, or mean, velocity profile is shown in Figure 5 in comparison with a theoretical flat-plate profile wherein the skin-friction coefficient, C_F, is equal to 0.00405. The deviations between the theoretical profile and the experimental data are thought to result from the fact that fully developed turbulent flow has not yet been realized in the boundary layer.

In order to determine the magnitude of the local values of the streamwise velocity fluctuations, u', the experimentally determined average velocity at various heights in the boundary layer was subtracted from each of the 21 individual profiles, and the deviations from the mean were recorded. The average value of the streamwise fluctuations, u', at any height in the boundary layer should be zero if sufficient samples are measured. In the present case, the average value of the u' fluctuations at any height was never greater than 1 percent of the free-stream velocity, which indicates that a sufficient number of profiles, 21, had been measured to obtain a valid statistical average. With this assurance, the root-mean-square values of the fluctuations at any height were calculated and are shown in Figure 6. Examination of this figure shows an apparent anomaly at the height $y/\delta = 0.65$, where the value of the nondimensionalized streamwise fluctuations, u'/U, is much greater than might be expected. Further reference to the photographs of Figure 4 reveals that it is at this height that the predominant perturbations occur in the profiles. It can also be seen from the smoke filaments shown in these photographs, particularly photograph 4(a), that a nearly periodic oscillation exists at approximately the same height. It is felt, therefore, that the unusually high level of turbulence at this height results from the early transition to turbulent flow of disturbances to the mean velocity caused by the Tollmien-Schlichting waves. This premise is further substantiated by the experimental results of Schubauer and Skramstad, who have shown that a 180-degree phase shift in direction of the streamwise fluctuations occurs at a height $y/\delta = 0.65$. Presumably, when the turbulence generated in this region is dissipated, and since it is no longer generated when fully developed turbulence is established, the high level at this height vanishes as the flow moves well downstream from the transition region.

In order to test this proposition that turbulence may be simultaneously generated at the wall and also at some height in the boundary layer as a result of amplified Tollmien-Schlichting waves, the plate was roughened by glueing a 6.0-inch strip of No. 180 sandpaper across the plate about 1 foot downstream of the leading edge. It was thought that this disturbance would cause the turbulence generated at the wall to spread more rapidly throughout the boundary layer and thereby preclude the transition caused by the amplification of the Tollmien-Schlichting waves.

With the roughness in place and with all other conditions the same, 36 smoke profiles were recorded at the measuring position. The data from these photographs were reduced in the manner previously described, and the results are shown in Figures 7 and 8. Here, a much closer agreement between the theory and the experimentally determined mean velocities can be seen Furthermore, the high turbulence level at $y/\delta = 0.65$ no longer appears. It may be concluded, therefore, that the

profile should have a shape more closely corresponding to that of fully developed turbulent flow. This conclusion is substantiated by the good agreement of Figure 7.

CONCLUDING REMARKS

The usefulness of the present technique of flow visualization as a means for the quantitative measurement of fluctuating or time-dependent flows has been demonstrated by the previous examples. By consecutive measurements at the same position, time-average, or mean, velocities can be measured and, from these, the instantaneous fluctuating velocities can be computed.

The device described is simple to construct and to operate, and no extensive maintenance is required. Furthermore, wide variations of application are possible by different orientations of the wire and by multiple flash photography.

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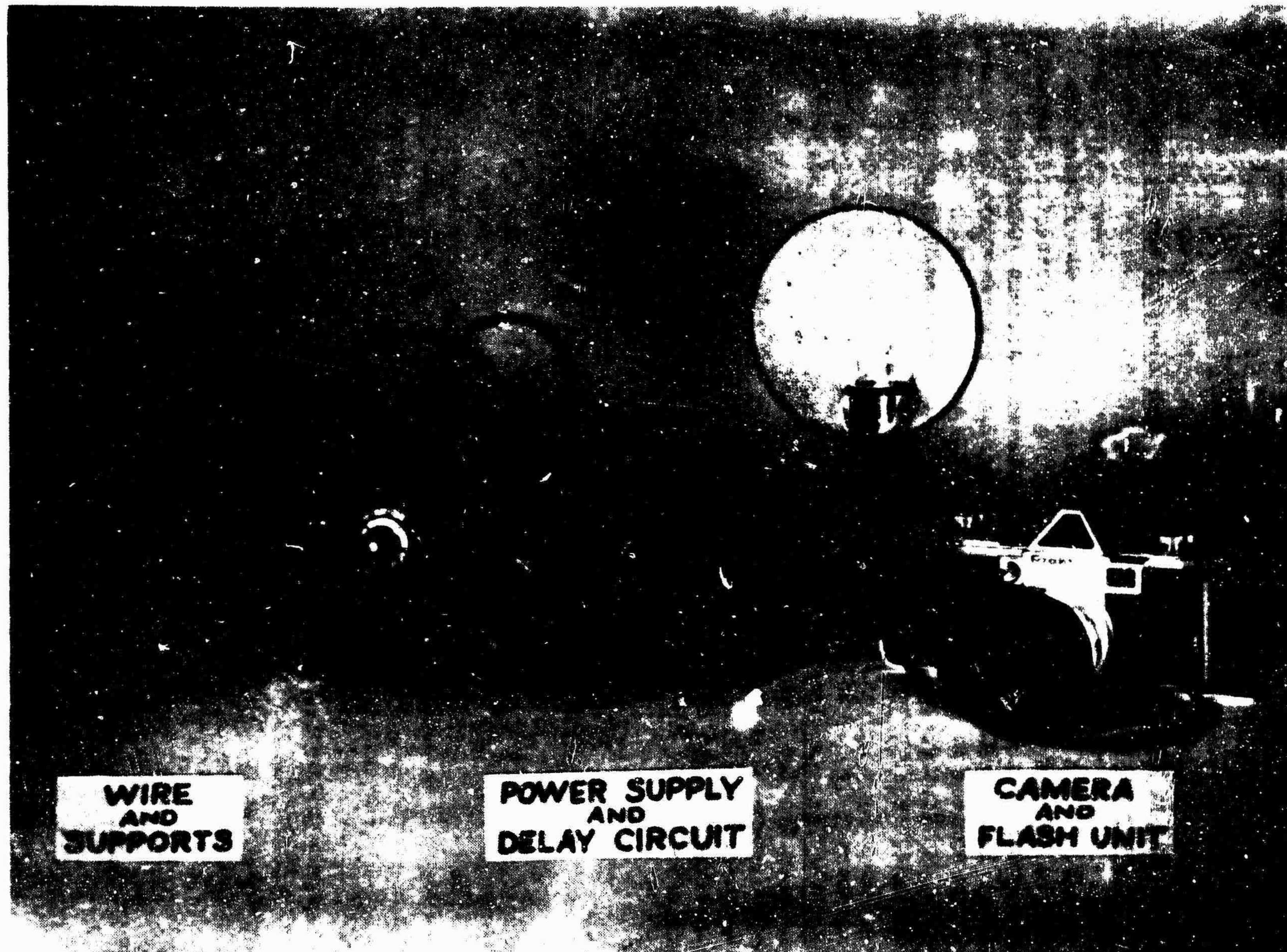

Figure 1. Apparatus for Visualizing and Photographing Boundary Layer Profiles.

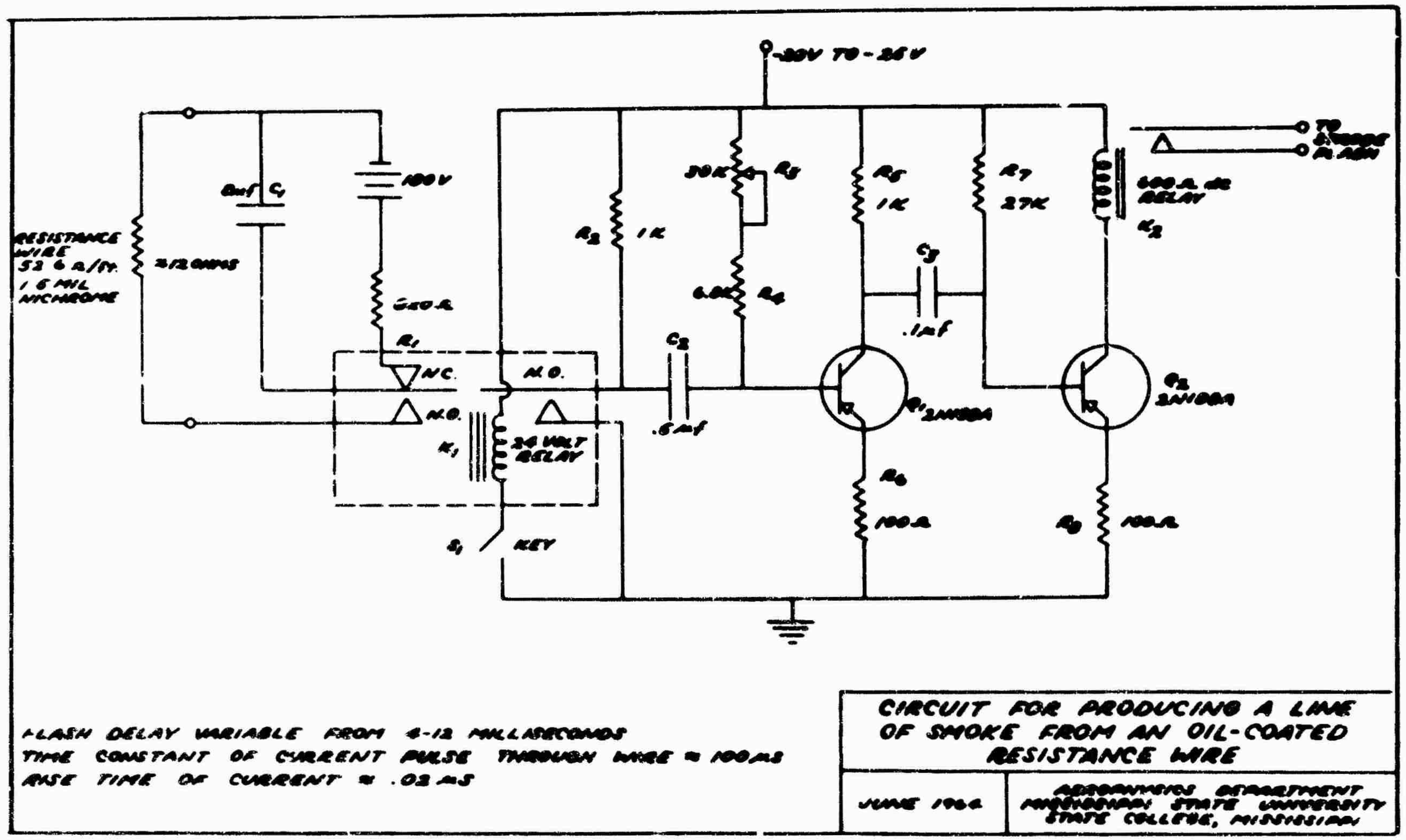

Figure 2. Circuit for Producing a Line of Smoke from an Oil-Coated Resistance Wire.

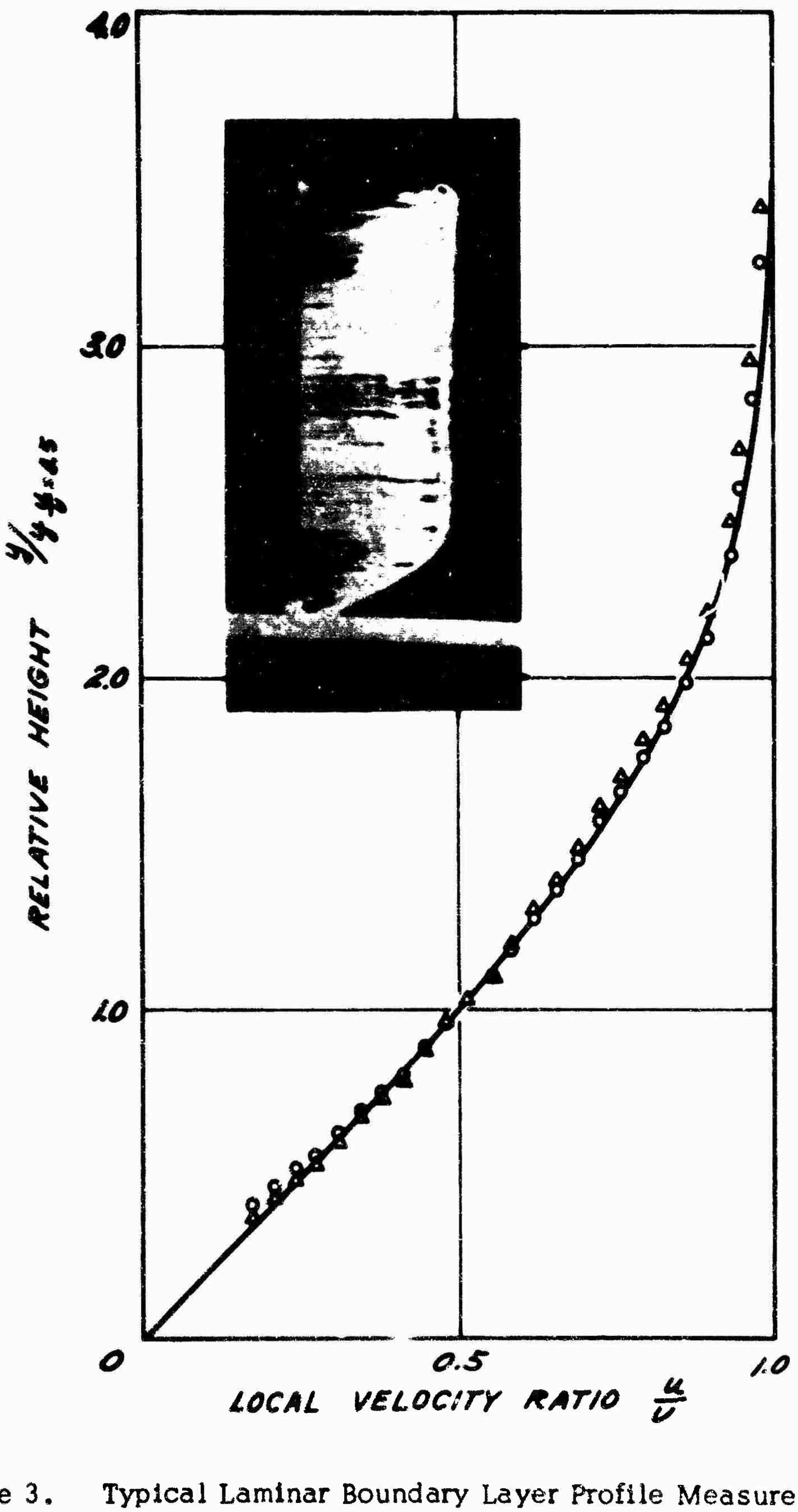

Figure 3. Typical Laminar Boundary Layer Profile Measurements.

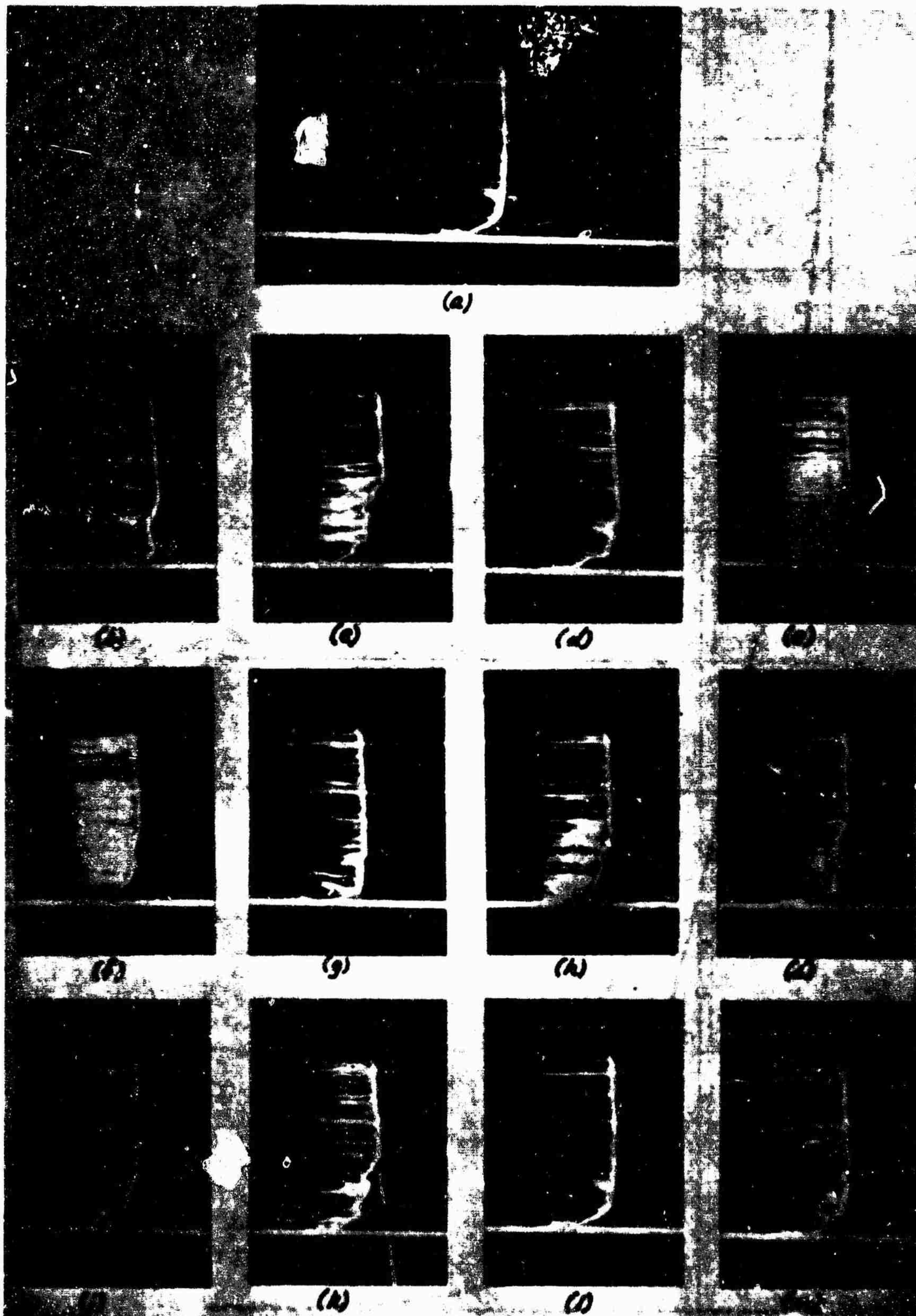

Figure 4. Some Examples of Instantaneous Measurements of the Turbulent Boundary Layer on a Flat Plate.

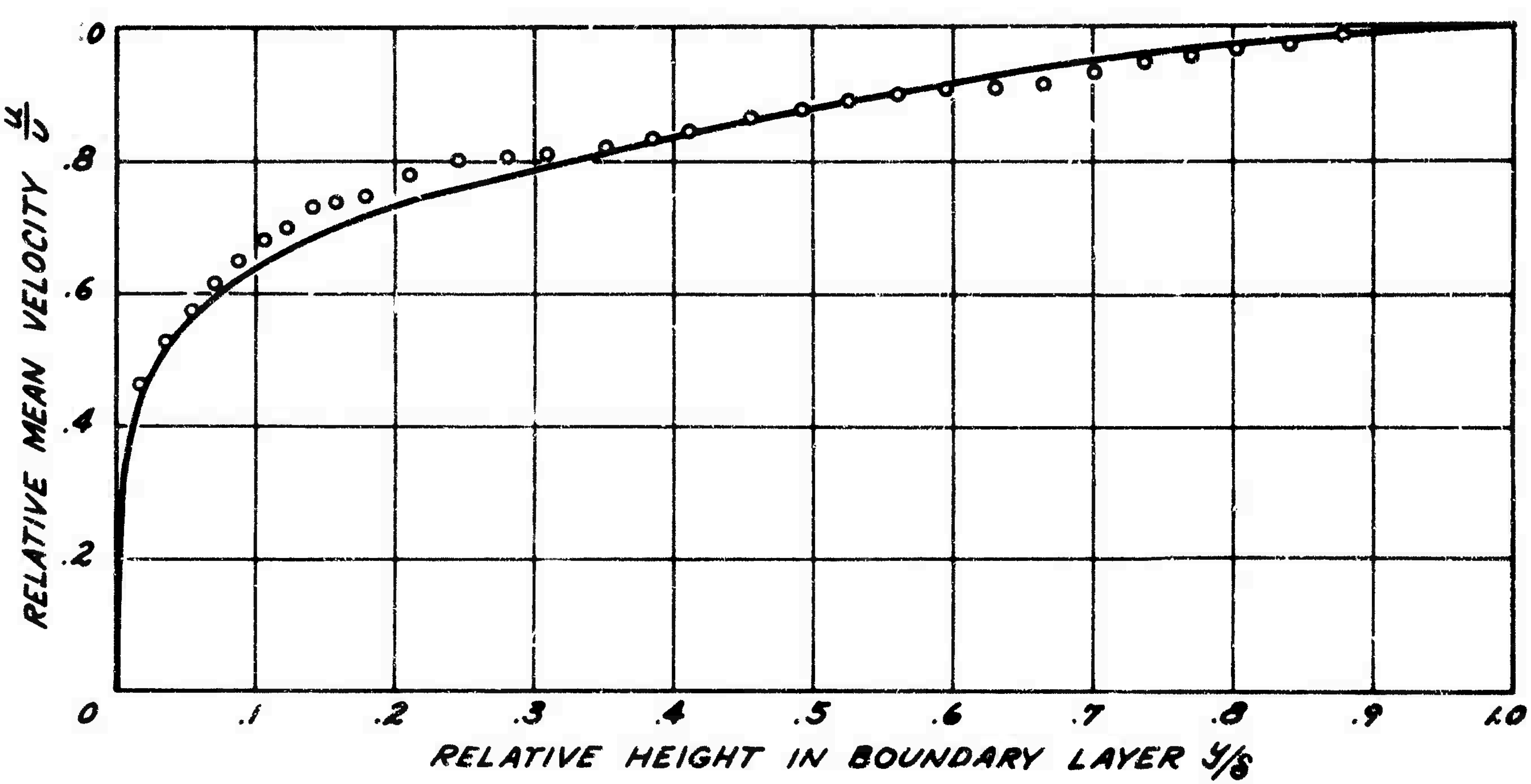

Figure 5. Comparison of Experimental and Theoretical Turbulent Mean Velocity Profiles after Natural Transition.

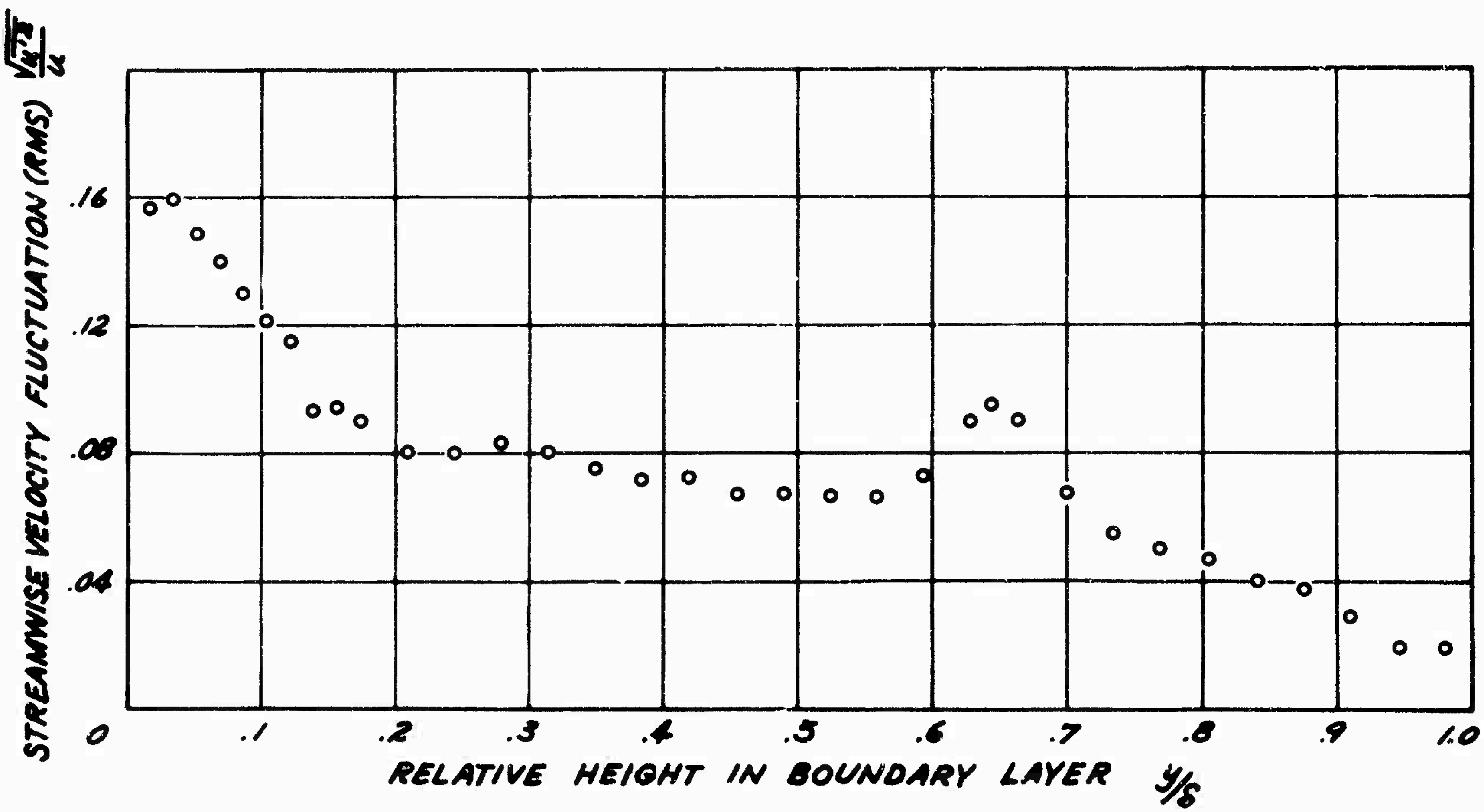

Figure 6. Streamwise Velocity Fluctuations in Turbulent Boundary Layer after Natural Transition.

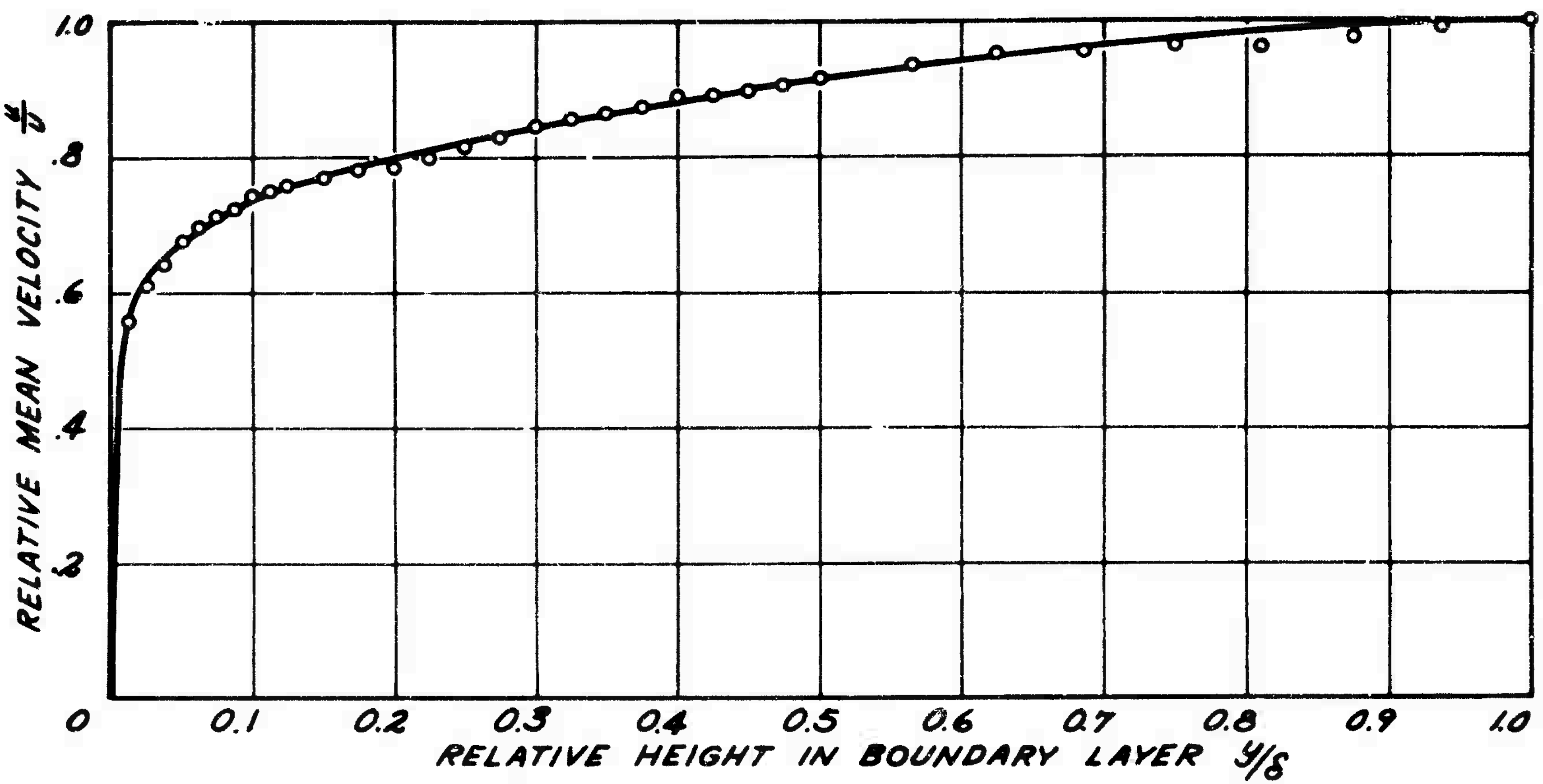

Figure 7. Comparison of Experimental and Theoretical Turbulent Mean Velocity Profiles with Artificially Stimulated Transition.

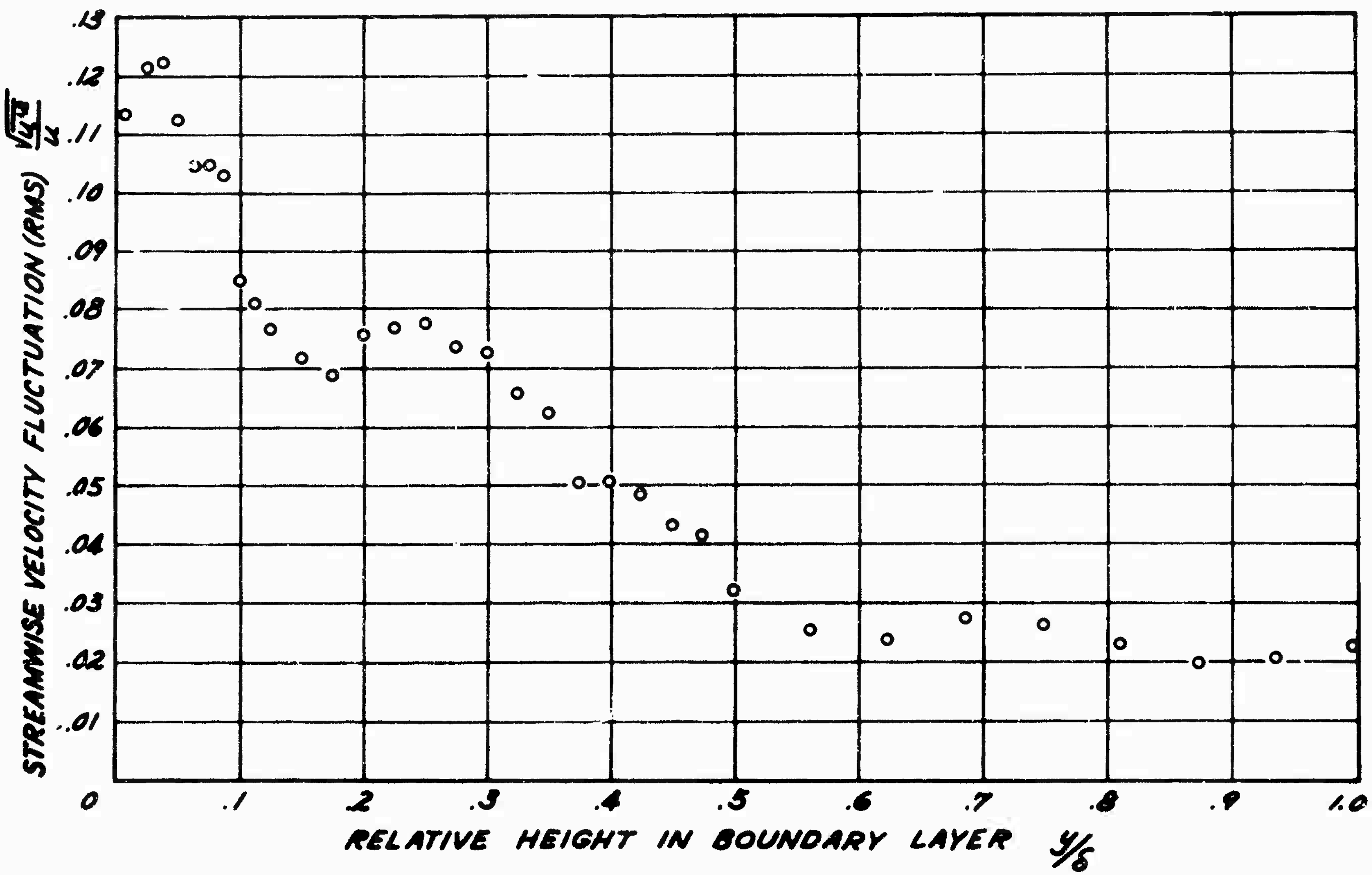

Figure 8. Streamwise Velocity Fluctuations in Turbulent Boundary Layer with Artificially Stimulated Transition.

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